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The Effects Of Multipath on the Measurement of Antenna Time Delays

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Introductory Remarks

Recent interest in potential errors associated with time delay measurements motivated the author to reprint a 1974 article that has not been widely circulated. It was one of the first articles at the Jet Propulsion Laboratory (JPL) to report on the errors associated with measuring time delays of signals propagating through the primary path of a large Cassegrain antenna.

It is appropriate here to give the reasons why antenna time delay work was of vital interest to JPL/NASA. Between 1973 and 1977, the ranges measured to a spacecraft at interplanetary distances from a worldwide network of Deep Space Stations (DSS's) were in disagreement by as much as 20 m (67 ns). Although 20 m might seem small when compared with the interplanetary range values of millions of kilometers that are measured from DSS's located in different parts of the world, the discrepancies were of concern to members of the Radio Science Team and the Navigation Team at JPL. A Ranging Accuracy Team was formed to investigate all possible sources of errors that might be causing the discrepancies between DSS's, and then to suggest ways to reduce the discrepancies by an order of magnitude.

After the Ranging Accuracy Team investigated all known sources of errors (including errors in knowing the station locations, calibration errors, and errors in accounting for delays associated with the atmosphere, the ionosphere, and charged particles in the interplanetary media), the causes of disagreement were still not known. The one area that had not yet been investigated was the time delay through the microwave Cassegrain antenna. The subject of antenna time delays was virtually new at that time. The author was assigned by the Ranging Accuracy Team to investigate potential errors caused by the Deep Space Network's (DSN's) Cassegrain antennas.

After many studies and experimental measurements of the delays through the Cassegrain antenna path, the cause of the discrepancies was finally pinpointed to effects of multipath signals on a particular method known as the zero delay device (ZDD) method. The ZDD method involved placing a probe (horn) on the main reflector. It was not previously known that, when weak multipath signals reflect from other off-path antenna structures and then return to combine with the primary path signal, surprisingly large errors in the measurement of range (time delay) can occur. The errors can be positive or negative depending on the phase of the multipath signal when it combined with the primary signal. The errors can be such as to muse the measured time delay to be shorter than the geometric optics (free-space) delay, thereby implying that the signal is trawling faster than the speed of light. After extensive experimental work on several types of Cassegrain antennas, multipath signals were conclusively found to be the major cause of the measurement errors. Through the use of a FM/CW time-domain technique, the locations and magnitudes of multipath sources were positively identified [S18], In addition, the FM/CW technique enabled multipath signals to be gated out so that only the primary signal delay was measured.

Further experimental and theoretical work showed that even though the multipath effects are large for a probe on the surface of the main reflector, in the far field the multipath signals combine in random phase and tend to cancel each other out. Experiments with a spacecraft confirmed that, in the far field, antenna multi path signals only caused about 3 ns of range error at S-band [S5], and the errors were 1 ns or smaller at X-band [S15]. It was shown by Cha et al. [S11] that, in the absence of multipath, the time delay of a CW signal propagating through the Cassegrain antenna path is equal to the geometric optic path length divided by the velocity of light. For a focused Cassegrain antenna, the paths have [lie same lengths for all rays radiating from the phase center of the transmit horn to an aperture plane in the far field.

Concurrent studies also revealed that discrepancies in measurements of time delays can also occur wilt'u ranging through a ground station system below the antenna feedhorn. Waveguides, filters, and cable.s in the station's uplink and downlink paths are often mismatched and, tj]c.rc.fore., set up multiple reflections. Studies showed that time delay measurement errors, similar to those caused by multipath signals, can also be produced by multiple reflections inside transmission lines. It has been shown from both theoretical and experimental data that the errors can be either positive or negative [S3].

Group delay standards [S6] were developed for the purpose of comparing the accuracies of different tit ne-delay measurement methods, including the. (1) modulation pulse delay tile.asulclllcnt method with an HP 8360A computing counter, (2) pulse technique with a Rantec time delay indicator, (3) time domain technique with a Scientific Atlanta fault locator, (4) phase-slope method with the HP 8542A automatic network analyzer, (S) range code modulation technique using the J]'], mu-ranging machine, and (6) pulse RF burst technique developed by the former National Bureau of Standards. Most of the results of the.se comparison studies are presented in [S6].

Methods requiring pulses with fast rise times seemed to be especially prone to errors (or clism."panties) when measurements were made on paths that had more than 6 dB of loss or when the paths were dispersive. The results were sometimes dependent on what part (50 or 90 percent) of the rise time was used and also on what detectors were used.

Some techniques inherently have the advantage of being more accurate than others because of their bandwidth (sometimes called aperture). When the bandwidth is small, such as in the case of the JPL ranging system (bandwidth is about 1 MHz), the errors due. to multiple reflections or multipath can be very large.. When the bandwidth (aperture) is small, the range envelope delay measurement comes close to being the same as a group delay measurement.

These discoveries led to the eventual development of a new "translator calibration technique" that has been and is still being used to calibrate ground station delays as part of the process of determining the range to a spacecraft [S7]. After implementation at all DSS's, the new calibration method led to an immediate improvement in agreement between range values measured throughout the DSN. In 1977, the Ranging Accuracy Team leader announced that during several days of ranging to the Mercury-Venus- Mars (MVM) 73 space.craft as it encountered Mars, an agreement of 3-5 m had been observed cm the range to the spacecraft as determined from all stations in the DSN. When one considers that the Earth-to-spacecraft range is in the millions of kilometers, this result is remarkable. It should be pointed out this achievement was obtained with stations operating with both 26-m- and 64-m-diameter Cassegrain antennas that had considerably different antenna path lengths. Account was taken of differences in delays due to the atmosphere, ionosphere, charged particles in the interplanetary media, and station locations. 64-m antennas *

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The following reprinted article presents the theory and experimental verifications of the relationship of multipath signal strength and differential path lengths to group delay measurement errors. It shows that even when the multipath signal is. 20 dB relative to the strength of the primary wave on a Cassegrain antenna, the errors can become very large. Although the theory presented in the article was originally intended for JPL applications, it is the author's hope that the material presented will be useful for other purposes. The curves presented in the article might be useful for evaluating potential errors in performing time

* measurements showed that multipath-related errors on 26-m antennas were an order of magnitude smaller than on 64-m antennas [S16]. Hence during this time period, the ~~previously~~ described

ZDD method ~~continued~~ was still used to calibrate delay measurements in a laboratory room test setup. If transmit-anti-rcce.ive. horn equipment is set up in a laboratory, rather than in an anechoic chamber, it might be the case that multipath signals originate from the main beam or sidelobe of a transmit horn and are multiply reflected within the room's walls, ceiling, or floor. When these multiply reflected waves finally combine with the primary signal that has traveled directly from the transmit horn to the receive horn, errors in time delay measurements can occur.

The results of the reprinted article have been confirmed experimentally, not only through tests described in the article, but also by many subsequent experiments described in the. supplementary references.

Supplementary References:

"l'he following 20 additional references concern antenna and ground-station time-delay measurement work clone at JPL after the elate of publication of the reprinted article. These articles, listed in chronological order, provide additional experimental data supporting the theory and equations presented in the reprinted article. Any of the JPL articles may be obtained from the Document Review Group, Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109.

S1. T. Y. Otoshi, "A Study of the Effects of Multipath on Two-Way Range," *The Deep Space Network Progress Report 42-2.5,* pp. 69-83, Jet Propulsion Laboratory, Pasadena, CA, February 15, 1975,

S2. "l'. Y. Otoshi, "S-Band Zero-Delay Device Multipath Tests on the 64-meter Antenna at DSS 43, DSS 63, and DSS 14," *The Deep Space Network Progress Report 42-29,* pp. *20-32,* Jet Propulsion Laboratory, Pasadena, CA, October 15, 1975.

S3. R. W. Beatty and T. Y. Otoshi, "Effect of Discontinuities on the. Group Delay of a Microwave. Transmission Line," *IEEE Trans. on Microwave Theory and Techniques*, Vol. MTT-23, No. 11, pp. 919-923, November 1975.

This article discusses the effects of multiple reflections in cables or waveguides on the measurement of the group delay of a transmission line.

S4. "T. Y. Otoshi (Editor), "A Collection of Articles on S/X-Band Experiment Zero Delay Ranging Tests," Technical Memorandum 33-747, Vol. 1, Jet Propulsion Laboratory, Pasadena, CA, November 1975.

S5. T. Y. Otoshi and D. L. Brunn, "Multipath Tests on 64-m Antenna Using the Viking Orbiter- 1 and -2 Spacecraft as Far-Field Illuminators," *The Deep Space Network Progress Report* 42-31, pp. 41-49, Jet Propulsion Laboratory, Pasadena, CA, February 15, 1976,

This article describes results of far-field multipath tests at S-band.

S6. T. Y. Otoshi and R. W. Beatty, "Development and Evaluation of a Set of Group Delay Standards," *IEEE Trans. on Instrumentation and Measurement*, Vol. IM-25, No. 4, pp. 335-342, December 1976.

This article compares several different measurement methods and presents the errors associated with each technique.

S7. T. Komarek and T. Otoshi, "Terminology of Ranging Measurements and DSS Calibrations," *The Deep Space Network Progress Report 42-36,* pp. 35-40, Jet Propulsion Laboratory, Pasadena, CA, December 15, 1976.

S8. T. Y. Otoshi, P. D. Batelaan, K. B. Wallace, and F. Ibanez, "Calibration of Block 4 Translator Path Delays at DSS 14 and CTA 21," *The Deep Space Network Progress Report 42-37*, pp. 188–197, Jet Propulsion Laboratory, Pasadena, CA, February 15, 1977,

S9. T. Y. Otoshi, R, B. Lyon, and M. France, "A Method for Measuring Group Time Delay Through a Feed Hem," *The Deep Space Network Progress Report* 42-44, pp. 82-89, Jet Propulsion Laboratory, Pasadena, CA, April 15, 1978.

Misprint: λ_0 in the numerator of the equation shown in Fig. 5 should be replaced by $\lambda_c(x)$. Results presented were based on the correct equation.

S 10. T. Y. Otoshi and K, R. Weld, "Updated Z-Corrections for 64-m DSS Ground Station Delay Calibrations," *The Deep Space Network Progress Report 42-47*, pp. 77-84, Jet Propulsion Laboratory, Pasadena, CA, October 15, 1978,

S11. A. G. Cha, W, V. T. Rusch, and T. Y. Otoshi, "Microwave Delay Characteristics of Cassegrainian Antennas," *IEEE Trans. on Antennas and Propagation*, Vol. AP-26, No. 6, pp. 860-865, November 1978.

This article deals with fundamentals of time delays of Cassegrain antennas.

S 12. T. Y. Otoshi, "Definition of Antenna Microwave Time Delay for VLBI Clock Synchronization," *The Deep Space Network Progress Report 42-49*, pp. 45–56, Jet Propulsion Laboratory, Pasadena, CA, February 15, 1979.

S 13. T. Y. Otoshi and W. V. T. Rusch, "Multipath Effects on the Time Delays of Microwave Cassegrainian Antennas," *The*

Deep Space Network Progress Report *42-50,* pp. *52-55,* Jet Propulsion Laboratory, Pasadena, CA, April 15, 1979,

S14. T. Y. Otoshi and T. Taylor, "An Experimental Investigation of the Effects of Antenna Pointing Errors on Range Delay s," *The Deep Space Network Progress Report 42-50,* pp. 141–147, Jet Propulsion Laboratory, Pasadena, CA, October 15, 1979.

S15. D. W. Green, "Validation of Roundtrip Charged Particle Calibrations Derived from S- and X-Band Doppler via DRVID Measurement," *The Deep Space Network Progress Report 42-50,* pp. 30--40, Jet Propulsion Laboratory, Pasadena, CA, February 15, 1980,

This article presents the result of a multipath test conducted on the 64-m antenna at X-band using the Voyager 1 spacecraft as the far-field illuminator. The test was conducted by Otoshi.

S 16. T. Y. Otoshi, "Experimental Investigation of the Effects of Antenna Pointing Errors on Range Delays (Part II)," The Deep *Space Network Progress Report 42-56,* pp. 143-146, Jet Propulsion Laboratory, Pasadena, CA, April 15, 1980.

S 17. T. Y. Otoshi and W, V, T, Rusch, "Multipath Effects on the Time Delays of Microwave Cassegrainian Antennas," *IEEE 1980 international Symposium Digest—Antennas and Propagation,* Vol. II, 80 CH 1557 -8AP, pp. 457-460, June 1980.

S18. T. Y. Otoshi, "An FM/CW Method for the Measurement of Time Delays of Large Cassegrain Antennas, " The *Telecommunications and Data Acquisition Progress Report 42-66,* pp. 49–59, Jet Propulsion Laboratory, Pasadena, CA, December 15, 1981.

This article provides experimental verification of the existence of multipath sources on a large antenna.

S 19. T. Y. Otoshi and L. E. Young, "An Experimental Investigation of the Changes of VLBI Time Delays Due to Antenna Structural Deformations," *The Telecommunications and Data Acquisition Progress Report 42-68*, pp. 8–1 6, Jet Propulsion Laboratory, Pasadena, CA, April 15, 1982.

S20. T. Y. Otoshi, W. V. T. Rusch, and I.. E. Young, "VLBI Collimation-Tower Technique for Time-Delay Studies of a Large Ground-Station Communications Antenna," *IEEE Trans. on Antennas and Propagation*, Vol. AP-33, No. 5, pp. 549–556, May 1985.

The following two excellent references are from non-JPL authors and should be consulted for fundamentals and errors associated with different delay measurement techniques.

S21. D. Ellerbruch, "Techniques for Measuring Time Delay," *Lecture Notes for the Phase Shift Measurements Seminar by NBS Staff Members, NBS* Rep. 9280, Boulder, CO, June 1967.

S22. H. Vi fian, *Group Delay, Delay Distortion, and its Measurement*, Ph.D. thesis, Swiss Federal Institute of Technology, Zurich, Switzerland, November 1972. (English version available via NASA RECON accession number N75- 27214.)